University of Groningen

Why growth rate differences persist

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IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2006

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Rensman, M. (2006). *Why growth rate differences persist: International technology diffusion in the long run*. [Thesis fully internal (DIV), University of Groningen]. s.n.

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Chapter 4

International technology diffusion, 1956-1996

4.1 Introduction

To what extent do differences in technology diffusion affect economic growth differences, given that countries have different technology systems and innovation systems? What role does R&D play for this technology diffusion? The current chapter logically follows the discussion in Chapter 3, which examined long run changes in technology systems and innovation systems. Now the impact of technology diffusion is made explicit by means of estimation of a formal macro-economic growth model. In this model, a technology gap gives a follower country a potential to catch up in technology, and ultimately, increase productivity growth. Own R&D effort may help to reduce the technology gap, as R&D provides capacity to absorb foreign technology. But countries differ in the extent to which R&D reduces their technology gap. This might be explained by differences in their technology systems and innovation systems.

Section 4.2 describes the macro-economic growth model. The model is estimated for France, Germany and the UK in the post-war period. Estimations are carried out for both the total market sector and the manufacturing sector of the three countries. The US is the presumed productivity and technology leader. Advanced technology is transferred from the US to the three European economies. The estimations should show how the three countries differ in absorbing US technology. The underlying data set is reviewed in Section 4.3. Appendix B.2 presents the time series. Section 4.4 describes the time series properties and estimation method. I discuss the estimation results and their economic implications in Section 4.5. Section 4.6 concludes.

4.2 The model

The current section presents a formal macro-economic growth model with international technology diffusion.[1] In the model, R&D is assigned a crucial role. R&D investments by the follower country enhance absorption of foreign leading technology. A country needs to invest resources in order to learn, master and adapt foreign knowledge.[2] Hence, international technology diffusion is not costless, following the economic-historical view. Furthermore, foreign knowledge has to be adapted to local circumstances as knowledge is often tacit and country-specific.

The model is based on endogenous growth theory, as described by Aghion and Howitt (1998a). In this growth theory, technological change is a major engine for economic growth. However, Aghion and Howitt (1998a) focus on domestic innovation as the driving force for growth. Interaction between countries and international technology diffusion are not elaborated extensively. The growth model developed in the current section assumes international technology diffusion be the driving force behind catching up and productivity growth. In this respect, it resembles the model of Howitt (2000).

It is assumed that the technology system and innovation system are more or less fixed, in order to disentangle the impact of technology diffusion and R&D from these driving forces in the very long run. I also assume that the immediate effect of R&D investments on the innovation system is negligible. This assumption seems to be reasonable with a time horizon that is relatively short in historical perspective, up to a number of decades. Within such a time horizon, R&D is supposed to be an input necessary to exploit the potential of social capability currently available in the economy.

Figure 4.1 displays the diffusion mechanism for a follower country as described by the current growth model. The symbols of the variables in

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[1] This model is developed in Rensman and Kuper (2000).

[2] Here, R&D has the same function as human capital has in the model of Nelson and Phelps (1966). It also implies that R&D has a dual role: it is not only an input in the innovation process, but it also increases the ability to learn about knowledge in the outside world (Cohen and Levinthal, 1989).

Figure 4.1: Diffusion mechanism at macro-economic level

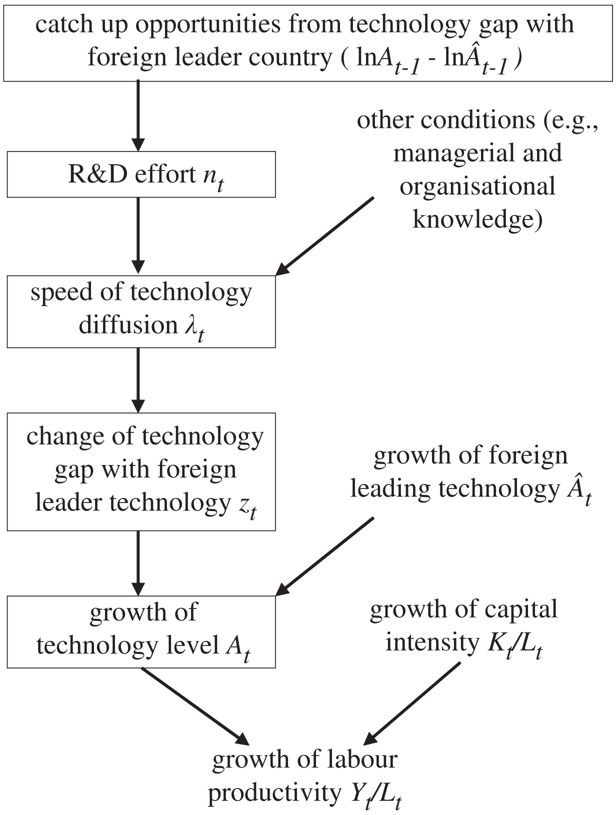

Figure 4.1 are used in the model and listed in Appendix A.

In the model, technology is transferred from a technology leader to a follower country during a transition to the long run equilibrium.[3] The average technology level A of the follower increases with the absorption of foreign technology $\hat{A}$. The speed of absorption is influenced by the follower's R&D effort, until the steady state growth rate of technology is achieved. Other factors, for instance managerial and organisational knowledge, are given but may also hamper or attribute to the speed of diffusion.

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[3] This is a special case of a general model with mutual technology spillovers; see Aghion and Howitt (1998a, p.421) and Howitt (2000).

In the long run, all possibilities to catch up with the leader by means of R&D are deployed, so that the technology gap will be constant. This long run gap is not necessarily zero, as countries differ in technology systems and innovation systems. Therefore the leader and follower may have a different steady state technology levels. But if the technology leader continues to grow, the follower has to follow at the same rate if the technology gap potential does not contribute to growth any more. Therefore the growth of the follower's technology level depends on the growth of the leader's technology level.

In the end, the growth of the technology level, in conjunction with conventional capital investments, determines labour productivity growth. The core idea of the model is that because of international technology diffusion from leader to follower with help of R&D, technology catching up may occur, ultimately leading to higher productivity growth. The working of the model is discussed in a formal way in the following subsections. I describe macro-economic production and capital accumulation, and more extensively, international technology diffusion. Then I present a testable specification of the model.

4.2.1 Aggregate production, technology and capital

The micro-economic incentives for firms to innovate modeled by Aghion and Howitt (1998a) are essential to the endogenous evolvement of technology and economic growth in the aggregate economy. These incentives are captured by the aggregate production function. In this aggregate production function, domestic income is divided between gross investment I_t, consumption C_t and research N_t. This income is generated by production according to the production function:

$$Y_t = A_t L_t k_t^{\alpha},$$

where A_t is the average quality level, or technology level. L_t is labour input, and $k_t \equiv K_t/(A_t L_t)$ is capital stock in efficiency units of labour. The parameter α measures the share of capital in output.

Define labour productivity $y_t \equiv Y_t/L_t$ and let the growth rate of a variable be denoted by g. The productivity growth equation is

$$g_{y,t} = g_{A,t} + \alpha g_{k,t}. \tag{4.1}$$

This states that growth of labour productivity is driven by capital accumulation and technological progress. Capital accumulation is important, following the economic-historical view, and complementary to technological change. The second term on the right-hand side of Equation (4.1) is the rate of growth of capital per efficiency unit of labour k_t, where

$$g_{k,t} = \frac{dk_t/dt}{k_t} = g_{K,t} - (g_{A,t} + g_{L,t}) .$$

Assuming a constant rate of depreciation of capital goods, δ, and defining $i_t \equiv I_t/K_t$, this can be written as:

$$\frac{dk_t/dt}{k_t} = i_t - (\delta + g_{A,t} + g_{L,t}) . \tag{4.2}$$

4.2.2 International technology diffusion

Define $\hat{A}_t$ as the leading-edge technology, that is, the average technology level of the technological leader at time t.[4] The leading-edge technology grows at rate

$$g_{\hat{A},t} = \frac{d\hat{A}_t/dt}{\hat{A}_t} = \hat{\sigma}\hat{\phi}_t,$$

where $\hat{\sigma}$ is the size of the innovations in the leader country, and $\hat{\phi}_t$ the arrival rate at which these innovations emerge.

The average technology level A_t of a follower country is lower than the leading-edge technology level $\hat{A}_t$. A_t will grow with technology diffusion from the leader. The arrival of new blueprints will gradually replace existing technology A_t with the leading-edge technology $\hat{A}_t$. Hence, the long run change in productivity dA_t/dt equals the arrival rate of innovations ϕ_t times the average change of technology $\hat{A}_t - A_t$:

$$\frac{dA_t}{dt} = \phi_t \left(\hat{A}_t - A_t\right)$$

or, in growth rates,

$$g_{A,t} = \frac{dA_t/dt}{A_t} = \phi_t (\Omega_t - 1) , \tag{4.3}$$

with $\Omega_t \equiv \hat{A}_t/A_t$. Ω_t is the technology gap of the follower with the leader country, or the follower's distance to the technology frontier.[5]

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[4] The technology level is an average, as not all technologies in use in the country need to be leading technologies.

[5] Note that the so called technology gap models of among others Fagerberg (1988) focus on gaps in terms of labour productivity or production. In the current model, the technology gap is explicitly modeled in terms of differences in technology levels.

R&D efforts n may speed up the rate at which technologies from the leader arrive in the follower country:

$$\phi_t = \phi_t(n_t). \tag{4.4}$$

In the long run, the technology gap Ω_t is assumed to converge to a constant (though not necessarily zero). That is, its long run growth rate is zero. This implies that growth rates of the technology levels of both countries are equal to each other:

$$\begin{aligned} \frac{d\Omega_t/dt}{\Omega_t} &= 0 \\ \Longleftrightarrow \frac{d\hat{A}_t/dt}{\hat{A}_t} - \frac{dA_t/dt}{A_t} &= 0 \\ \Longleftrightarrow \hat{\sigma}\hat{\phi}_t - \phi_t\,(\Omega_t - 1) &= 0. \end{aligned}$$

In the long run, innovations will arrive at the same rate in both countries, so $\hat{\phi}_t = \phi_t = \phi$. Then

$$\begin{aligned} \hat{\sigma}\phi &= \phi(\Omega - 1) \\ \Longleftrightarrow \Omega &= 1 + \hat{\sigma}. \end{aligned}$$

4.2.3 Empirical specification

Productivity growth The productivity growth function (4.1) is based on production with Harrod neutral technological progress. In the Cobb Douglas production function, neutrality of technological progress in the sense of Harrod is equivalent to the Hicks variant.[6] For convenience, the productivity growth function is rewritten to a form with Hicks neutral technological progress:

$$g_{y,t} = g_{A_t} + \alpha g_{(K/L)_t} = (1-\alpha) g_{A_t} + \alpha[g_{(K/L)_t} + g_{A_t}]. \tag{4.5}$$

In empirical application, the growth rates are calculated in log-differences.[7] So for any follower country j, productivity growth $\Delta \ln y_t^j$ depends on the

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[6] In the growth literature, it is commonly assumed technological progress is labour augmenting in a Cobb-Douglas production function, as this makes it easier to derive the steady state. Aghion and Howitt (1998a) argue that the nature of technological progress is actually not fixed beforehand. So Hicks neutrality cannot be excluded. In any case, the assumption implies that it is not possible to draw conclusions from empirical application on the nature of technological progress.

[7] Assuming that the year-to-year changes are not too large, growth rates can be calculated as log differences.

growth of capital intensity $\Delta \ln(K/L)_t^j$ and technology growth $\Delta \ln A_t^j$:

$$\Delta \ln y_t^j = (1-\alpha)\Delta \ln A_t^j + \alpha \left[\Delta \ln(K/L)_t^j + \Delta \ln A_t^j\right] + u_t. \tag{4.6}$$

This is the equation for productivity growth that is used in the estimation below. The capital share parameter α is expected to be positive, and its value should be around 0.30, according to growth studies like Mankiw et al. (1992).

Technology growth In the theoretical growth model, the growth of the technology level depends on the arrival rate of innovations ϕ_t and the change of technology $\hat{A}_t - A_t$. To come up with a testable specification, a somewhat different approach is used. Here, inevitably, some *ad hoc* assumptions have to be made.

Suppose there are m countries, each with their own level of technology A_t^j. Define the leading edge technology as:

$$\ln \hat{A}_t \equiv \sum_{j=1}^{m} \omega^j \ln A_t^j,$$

where ω^j is the importance of country j as a source of new technological ideas for other countries, and $\sum_j \omega^j = 1$. The weighting scheme ω^j needs to be known a priori. I suppose that one country k is the technological leader, so that $\omega^k = 1$, and $\ln \hat{A}_t = \ln A_t^k$. In empirical application, the US is chosen as the technology leader k in the post-war period. The US might be caught up by other countries, just like the UK was caught up by the US in the 19th century. Moreover, at industry level, leadership can vary across countries (see Chapter 5). Assuming that the US is the leader, is merely stating that it is a numeraire country to other countries. Then differences in diffusion and catching up (with respect to the US) between these follower countries will show up.

It is assumed that, in the long run, the technology gap $\Omega_t^j \equiv \hat{A}_t / A_t^j$ of a follower country j converges to a constant z^j:

$$-\ln \Omega_t^j = \ln A_t^j - \ln \hat{A}_t = z^j.$$

Then the long run growth rates of the technology levels of the leader and the follower are equal,

$$g_A^j = g_{\hat{A}}.$$

The long-run technology gap z^j, which is negative by definition as country j is lagging behind, is the empirical counterpart of Ω in the theoretical model.[8]

Now suppose (like in the theoretical model) that the change in the level of technology in country j depends on a change in the technology gap with the leader. I impose an ECM structure which has a tendency to converge to the long run.[9] The technology level of country j is defined as

$$\ln A_t^j = z^j + \ln \hat{A}_t.$$

The dynamics are captured by

$$\Delta \ln A_t^j = -\lambda_t^j \left(\ln A_{t-1}^j - \ln \hat{A}_{t-1} - z^j \right) + \beta \Delta \ln \hat{A}_t + u_t. \tag{4.7}$$

This is the equation of technology growth that is used in estimation. The term between brackets on the right-hand side of Equation (4.7) is the change in the technology gap. The second term is the rate of growth of the technology of the leader country, $g_{\hat{A},t}$. In the long run, when the gap z^j is constant, β should be equal to 1, i.e., growth rates of technology should be equal, similar to the theoretical model. Equation (4.7) is the empirical counterpart of Equation (4.3). In empirical application, the value of β is expected to lie between zero and one. If the economy is already near steady state, the value should be close to one. If not, the value might be smaller than one. But it might also happen that the long run technology gap z remains non-zero and negative, because technology systems and innovation systems differ across countries. Some leading technologies might not be appropriate to the follower, even if it tries to adapt it to its own circumstances.

The technology gap is supposed to reduce if the follower country conducts R&D in order absorb the leading edge technology. These R&D efforts are captured in the time-varying parameter λ_t^j in Equation (4.7). This parameter measures the speed of convergence of country j's technology to the leading-edge technology. Assume, freely on the basis of the theory on the determinants of the arrival rate of innovation ϕ_t, that the speed of convergence is influenced by R&D:

$$\lambda_t^j = \psi^j + \gamma^j [n_t^j], \tag{4.8}$$

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[8] Note that for follower country j, $0 < \Omega^j < 1$, so that $z^j < 0$.

[9] An error correction mechanism (ECM) describes how the dependent variable adjusts to its existing long-run trend. It explains how the long-run error will explain the movement of the dependent variable in the short run.

where n_t^j denotes R&D efforts by country j. For practical purposes and to capture scale effects, n_t^j is measured as the reciprocal of R&D productivity by the ratio of R&D resources N^j over production Y^j (cf. Aghion and Howitt, 1998a, p.418):[10]

$$n_t^j \equiv \frac{N_t^j}{Y_t^j}.$$

In empirical application, the R&D intensity is measured as (the log-level of) R&D expenses per unit of value added or alternatively as R&D employees per hour worked.

The idea underlying Equation (4.8) is that in order to adapt foreign technology, R&D investment is necessary for adoption and adaptation of foreign knowledge. It is expected that the R&D parameter γ^j is positive, as doing R&D provides absorptive capacity. Then given the technology gap in the previous year, R&D positively affects the speed of absorption. Other factors which are not specifically linked to R&D but may attribute to or hamper the process of adjustment are simply captured by the constant term ψ^j in Equation (4.8). One can think of, for instance, organisational and managerial knowledge, or knowledge not embodied in the R&D process itself. The composite speed parameter λ_t^j thus captures R&D and non-R&D forces affecting a country's speed of absorption. If the country lags behind technologically, then a positive value of the speed parameter λ_t^j signals convergence to the leading edge technology.

The productivity growth equation (4.6) and technology growth equation (4.7) with the speed of diffusion (4.8) are used in estimation below. The estimation is carried out for three Western European economies (France, Germany and the UK), which absorb US technology in the period 1956-1996. This estimation does not test the long run conditions, but the weaker assumption of a relationship between growth performance and technology diffusion. There might be no smooth convergence to the steady state, as an economy continuously experiences shocks in economic and technological conditions. Furthermore, as countries are supposed to differ in technology systems and innovation systems, growth

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[10] This meets Jones' (1995) criticism that the increasing scale of R&D efforts in the post-war period did not lead to a much higher growth rate. Because of increasing complexity of technology, the scale of R&D had to increase to keep the innovation rate constant; and because of increasing variety, the impact of a new product on production becomes smaller (Aghion and Howitt, 1998a, p.418).

rate differences are unlikely to disappear fully, even in de long run. This might only happen if the long run growth path shifts, that is, if the technology system or innovation system changes. A period of a few decades such as used in the estimation below is probably too short for fundamental changes in the technology system and the innovation system.

4.3 Data

This section presents time series on labour productivity, capital intensity, technology and R&D effort by the UK, France and Germany in the postwar period, with the US as the presumed technology leader. First I discuss the construction of proxies for the variables in Section 4.3.1. Section 4.3.2 shortly reviews the development of the time series.

4.3.1 Proxies for the variables

In the data the market economy as a whole and the manufacturing sector are distinguished.[11] This may reveal sectoral differences in productivity growth and technology diffusion. Such differences can partially explain aggregate growth performance. The data and its sources are given in Appendix B.2.

Labour productivity Labour productivity is calculated as value added per hour worked. These data are from O'Mahony (1999). Dividing output by hours worked accounts for international differences in part time work, which is preferred to head counts.

Capital intensity Capital intensity is measured as capital services per hour worked, from O'Mahony (1999). Data on capital services capture the implicit transaction costs of the actual input of capital in the production process. Capital goods are carriers of capital services, such as employees are carriers of human capital or labour services. The difference between capital and labour is that producers are usually owners of capital goods. When the capital good delivers services to its owner, no market transaction is recorded, in contrast to the hiring of labour. This implicit price of the capital service is measured by the user cost or rental price of capital (O'Mahony, 1999).

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[11] Non-market sectors (government, education and health) are excluded, as the model does not hold for these sectors.

Technology The technology level A is proxied by the stock of patent applications cumulated over 10 years. The data on annual patent applications after 1973 are from the OECD, and from various sources for the period before 1973 (see Appendix B.2). Patents do not cover all inventions, and not all inventions are patented. But as Griliches (1994) put it, the choice is between patents or no data at all for innovation output.

I made a number of choices in constructing the proxy for technology. First, I constructed patent stocks as annual flow data are more sensitive to changes in, for instance, administrative procedures at national patent offices and the international patent law such as in the 1970s.[12] Second, the stocks are constructed with patent application numbers cumulated over 10 years.[13] The choice for this period is more or less arbitrary. It is partly driven by the availability of the data (the time series for annual patent numbers starts around 1946), and partly by initial estimations of the growth model, which revealed that stocks with patents cumulated over 10 years generated more statistically significant results than, for instance, stocks cumulated over 5 years. Third, the stock is not scaled with output or employment, as this gives a *productivity* measure for technology. The aim of the model estimation is to show how technology affects on labour productivity. Fourth, the patent stock contains for both the market sector and the manufacturing sector the *total* domestic stock of patent applications. I assume that the domestic patent stock represents the total technology market for potential goods, open to all sectors. Hence the stock includes intranational technology diffusion between sectors.[14] Finally, the patents include applications from both foreigners and domestic residents. The stock represents the technology level available at a time t, and it does not matter whether this technology was originally foreign or domestic. What matters is that a perceived technology gap at a time t gives rise to R&D efforts to catch up at time $t+1$.

The technology gap $\left(\ln A_{t-1}^{j} - \ln \hat{A}_{t-1}\right)$ is the difference between cumulated patents in country j and the technology leader US. There are differences between countries in the incentive to patent, due to differences in granting procedures, policy, culture and economic factors. I assume that countries differ systematically in the incentive to patent and

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[12] This sensitivity is even larger for data on grants. Granting is dependent on what a patent office defines as a new idea and economic utility.

[13] The depreciation rate is assumed to be zero.

[14] The next chapter explicitly models intranational diffusion.

in the patent-invention ratio, so that the development of the technology gap systematically captures changes in exploiting catch up opportunities.

R&D R&D effort n is measured as business R&D expenditures per unit of value added, or alternatively, the number of R&D employees (researchers, scientists and engineers, RSE) per hour worked, using OECD data. R&D statistics do not cover all innovative input. Soft or tacit knowledge is generally not measured, and many small firms do not separately register their R&D expenditures. Still, R&D effort is an important part of total innovative effort, and I assume that R&D effort is proportional to total innovative effort. I apply both the log-level and the growth rate of R&D effort. Estimation will reveal which variant of n provides statistically significant results.

4.3.2 Comparative developments, 1956-1996

The time series for labour productivity, capital intensity, technology and R&D effort are presented in growth rates in Table 4.1, and in comparative levels (with US=100) in Figure 4.2 to 4.4. The comparative levels of the three European countries picture their backlog (or potential to catch up) with respect to the US.

Labour productivity In the three European countries, the annual labour productivity growth rate was higher in the manufacturing sector (4 to 4.7% between 1956 and 1996) than in the market sector as a whole (3.1 to 4%). Nevertheless, by 1996, their labour productivity levels with respect to the US were still lower in manufacturing (50 to 80% of the US level) than in the market sector (80 to 100%). Compared to the US, non-manufacturing sectors are important to the three European economies, particularly market services (Broadberry and O'Mahony, 2004). In order to understand macro-economic performance, it is therefore important to apply a sectoral view (Bernard and Jones, 1996b).

Comparative labour productivity levels in the market sector increased in particularly France and Germany. In manufacturing, catch up halted by the 1980s. By that time, US manufacturing was growing nearly as fast as the European economies. The economic literature suggests this is due to developments in US high tech industries. In the 1990s, ICT materialized in US labour productivity (Stiroh, 2002). The UK experienced the lowest growth in comparative level in both the market and manufacturing sector between 1956 and 1996. It moved slowly to nearly 80% of the American level in the market sector, and to 60% in manufacturing in the 1990s, only to fall back to 50% by 1996.

Capital intensity The European countries' comparative capital intensity levels rose in both the market sector and manufacturing, similarly

Table 4.1: Labour productivity, capital intensity and technology (average annual growth rates), 1956-1996

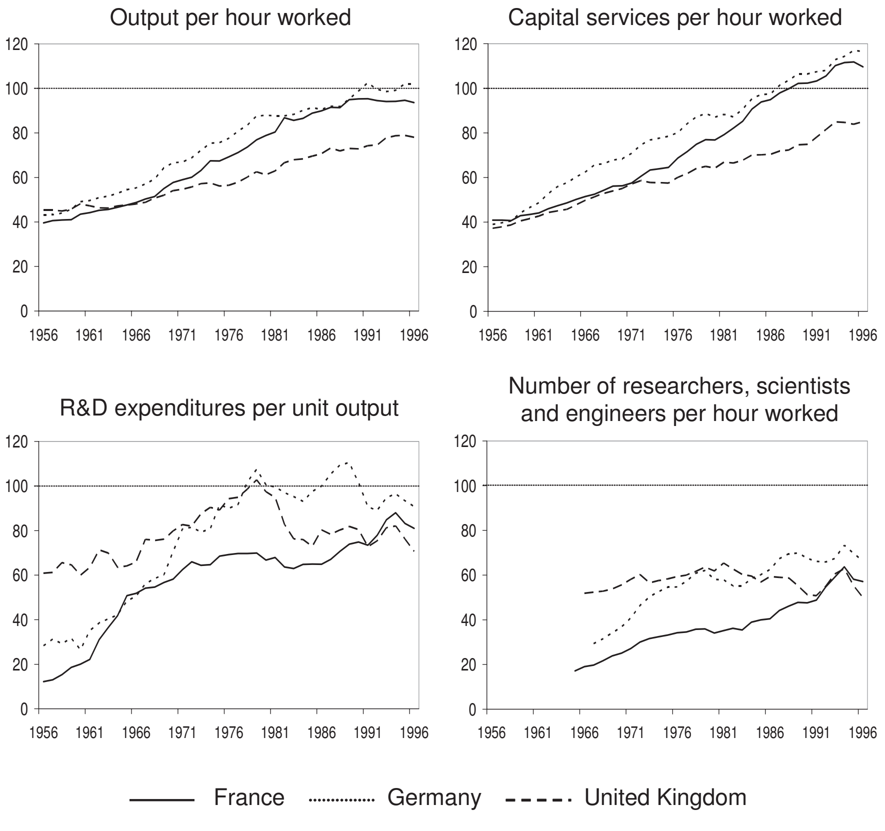
	Market sector				Manufacturing			
	Fra	Ger	UK	US	Fra	Ger	UK	US
	Value added per hour worked							
1956-73	5.4	5.7	4.0	2.6	6.2	6.2	5.0	3.0
1973-96	2.9	2.7	2.6	1.2	3.7	2.9	3.1	2.2
1966-96	3.6	3.4	3.0	1.4	4.3	3.6	3.8	2.4
1956-96	4.0	4.0	3.2	1.8	4.7	4.3	3.9	2.5
	Capital services per hour worked							
1956-73	5.3	6.7	5.3	2.7	6.3	6.9	4.9	2.7
1973-96	3.8	3.3	3.1	1.5	4.6	3.8	3.5	3.3
1966-96	4.4	3.9	3.7	1.9	4.9	4.2	3.9	3.4
1956-96	4.4	4.7	4.0	2.0	5.3	5.1	4.1	3.1
	Stock of patents cumulated over 10 years							
1956-73	3.7	$1.2^{(a)}$	3.1	1.8				
1973-96	2.1	1.7	1.8	2.8				
1966-96	2.2	$1.6^{(a)}$	2.0	2.6				
1956-96	2.8	$1.4^{(a)}$	2.3	2.4				
	R&D expenditures per unit of value added							
1956-73	9.9	6.1	2.2	0.1				
1973-96	1.7	1.3	-0.2	0.7	1.9	2.5	0.6	0.6
1966-96	1.2	1.7	-0.1	-0.3	1.1	2.5	0.3	-0.4
1956-96	5.2	3.4	0.8	0.4				
	Number of researchers per hour worked							
1973-96	5.1	3.7	2.0	2.5	5.8	4.7	3.3	3.1
1966-96	5.3	$4.4^{(b)}$	1.5	1.6				

(*a*) Series start in 1960.
(*b*) Series start in 1967.

to their labour productivity levels. By 1996, France and Germany had even surpassed the US in the market sector (110 to 120% of the US level), and France in manufacturing (110%). Apparently, the high comparative capital intensity of France and Germany did not induce correspondingly high comparative levels of labour productivity. The British comparative labour productivity performance, in contrast, seems to correspond with the development of its comparative capital intensity level.

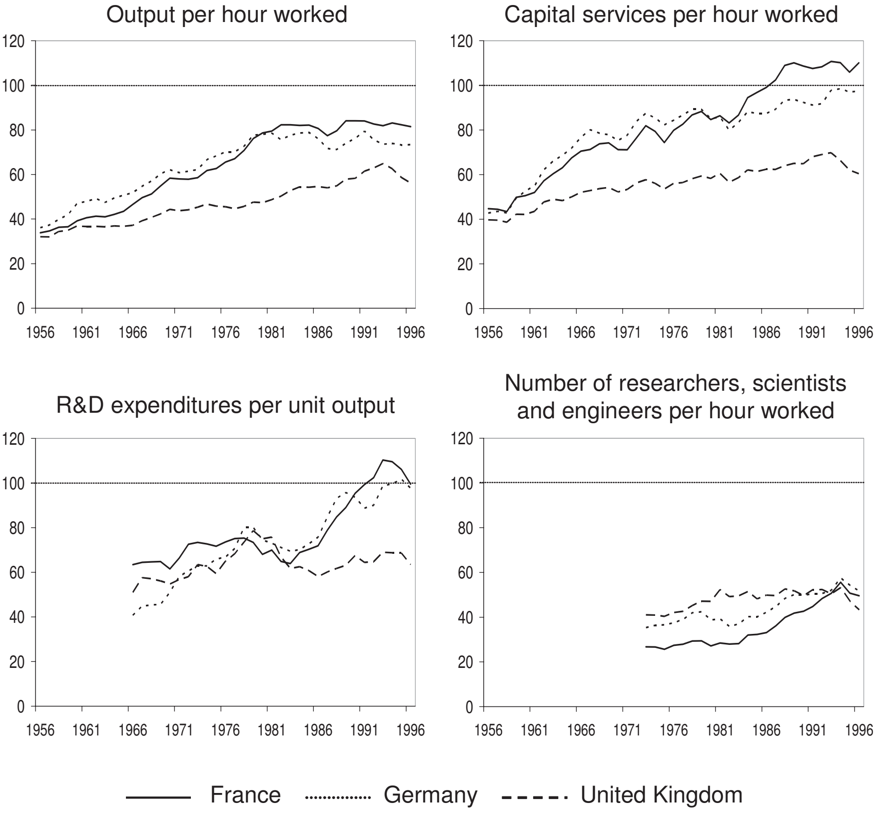
This suggests that in the UK conventional capital accumulation to generate economic growth is more important than in France and Germany. A possible explanation is the copying of American capital inten-

Figure 4.2: Labour productivity, capital intensity and research intensity in the market sector (US=100), 1956-1996



sive mass production systems in UK manufacturing (see Chapter 3). Another explanation is that France and Germany did not succeed to exploit their capital efficiently because of bottlenecks in economy or institutions (see for instance, Sicsic and Wyplosz, 1996, and Carlin, 1996). However, the economic-historical literature sketches a picture of a UK experiencing much larger bottlenecks (Bean and Crafts, 1996). Finally, the comparatively high US labour productivity level despite comparatively low capital intensity might also be driven by successful exploitation of its innovation potential in high tech industries. In any case, economic catching up does not appear be an automatic process of capital accumulation.

Figure 4.3: Labour productivity, capital intensity and research intensity in the manufacturing sector (US=100), 1956-1996

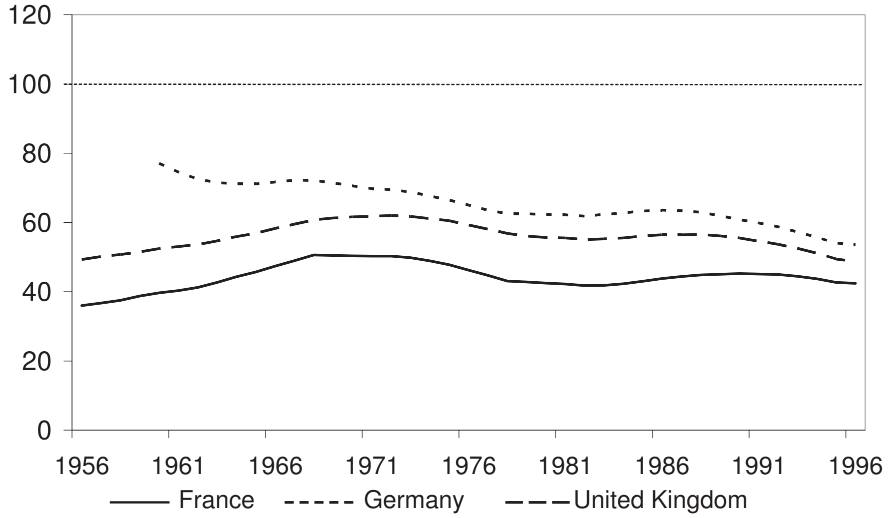

Output per hour worked

Capital services per hour worked

R&D expenditures per unit output

Number of researchers, scientists and engineers per hour worked

Figure 4.4: Stock of patent applications cumulated over 10 years (US=100), 1956-1996



Technology gap The technology gaps of France and the UK with respect to the US narrow gradually up to the 1970s, in contrast to the German stock (Figure 4.4). After 1973, the American patent stock expanded more quickly, probably due to the increase in the innovation rate in high tech US industries. This led to increasing technology gaps of the three European countries in the mid-1970s and after 1985. These developments suggest that the European countries do not catch up in technology, in contrast to their labour productivity. However, while their patent stocks were growing, the American stock was just growing slightly faster. Meanwhile, the European economies might well have absorbed US technology.

The UK has a higher comparative technology level but a lower comparative labour productivity and capital intensity level than France during the period under consideration. A possible explanation is that the UK did not succeed in exploiting its potential to catch up in technology to full extent. Nickell and Van Reenen (2001) argue that the UK has a high quality science base but does not succeed to commercialise it. Furthermore, the technology gap between the US and Germany increased already from the late 1950s on, although the German technology level remains above that of France and the UK. The development and utilization of its capital may have helped Germany to keep its productivity at a high comparative level. If so, the capital deepening before 1973 has counterbalanced the slow capital development after 1973 (see Carlin, 1996).

One conclusion is that one must distinguish between catching up in productivity and catching up in technology (Broadberry, 1994a; see also Chapter 3). Moreover, the developments in the European economies raise questions on the role of capital. Does capital strengthen the exploitation of technology (by means of embodiment) in order to increase productivity, or is it a substitute for technology? The macro-economic growth model in Section 4.2 assumes that capital is a complement to technology.

R&D efforts In 1956, the UK level of business R&D per unit of value added in the market sector was substantially higher than that of Germany and France (Figure 4.2). But the UK position deterioriated, particularly after the late 1970s. At the same time, its backwardness in productivity and capital intensity increased compared to the other two countries. In manufacturing, the R&D effort in the UK still resembled that of France and Germany in the late 1970s, only to fall far behind thereafter. In Germany and France, R&D intensities with respect to the US rose substantially, particularly in the Golden Age period to 1973. This was accompanied by a contemporaneous increase in their comparative labour productivity and capital intensity levels. If R&D is essential in providing absorptive capacity to absorb US technology, the labour productivity differences between the UK on the one hand and France and Germany on the other hand seem plausible.

R&D expenditures and the number of researchers, scientists and engineers (RSE) are highly correlated. In the market sector, the development of comparative RSE intensity levels resembles that of R&D expenditures. In manufacturing, comparative RSE intensities are about the same in all three European countries by the 1990s, in contrast to comparative R&D intensity levels. But above all, the comparative RSE intensity levels were substantially lower than the R&D intensity levels. These differences between R&D and RSE intensities may have consequences for their explanatory power in the estimation of the growth model.

4.4 Method

The estimation results of the growth model are sensitive to the time series properties of the underlying data, and the estimation method. Correlations between the dependent and explanatory variables, unit root tests and cointegration tests may reveal these time series properties. This section examines the correlations between the proxies (Section 4.4.1) and tests for unit roots in the time series (Section 4.4.2). Finally I discuss the estimation method (Section 4.4.3).

4.4.1 Correlations

High correlations between the proxies for the variables in the productivity growth function and the technology growth function do not imply causality, but support the assumptions made on the relationships in the growth model. Table 4.2 summarizes the pairwise correlations over the period 1956-1996.

I expect a correlation between labour productivity growth on the one hand and the growth of capital intensity and technology on the other hand. It appears that the correlation between labour productivity growth and capital intensity growth is highest when the latter variable is lagged one period, between 0.5 and 0.6. Moreover, the correlations have a positive sign, as I expect from the growth model. The correlation between productivity growth and technology growth is rather low, and signs differ across countries and sectors. Taking lags do not improve results. The low correlation is probably caused by the construction of the proxy for technology. The patent stocks show a smooth development, while labour productivity growth fluctuates over time.

Second, I expect technology growth in the follower countries to be correlated with their technology gap with the leader US, and with the technology growth in the US. The correlation with the technology gap with the US in the previous year is negative, as I expect from the model, though the correlation values are not very high (-0.2 to -0.5). The correlation between technology growth and the US technology growth is, as expected, positive and reasonably high (above 0.6).

Finally, the theoretical model predicts that R&D effort has a positive impact on the speed of absorption. Conditional on other forces, R&D effort is expected to be (negatively or positively) correlated with the technology gap in the previous year, and positively correlated with technology growth. Here I test R&D per unit of value added in log-levels

Table 4.2: Pairwise correlations, 1956-1996

		Correlation of labour productivity growth $\Delta \ln y_t^j$ with			
		$\Delta \ln(K/L)_t^j$	$\Delta \ln A_t^j$	$\Delta \ln(K/L)_{t-1}^j$	$\Delta \ln A_{t-1}^j$
Market economy	Fra	0.59	-0.13	0.55	-0.01
	Ger	0.48	-0.19	0.59	-0.18
	UK	0.10	0.12	0.47	0.15
Manufacturing	Fra	0.17	0.02	0.52	0.13
	Ger	0.22	-0.11	0.55	-0.13
	UK	-0.04	0.30	0.51	0.30
		Correlation of technology growth $\Delta \ln A_t^j$ with			
		technology gap with US ($\ln A_{t-1}^j - \ln \hat{A}_{t-1}$)		technology growth in US $\Delta \ln \hat{A}_t$	
For both sectors	Fra	-0.22		0.58	
	Ger	-0.52		0.78	
	UK	-0.34		0.65	
		Correlation of technology gap ($\ln A_{t-1}^j - \ln \hat{A}_{t-1}$) *with*		*Correlation of technology growth* $\Delta \ln A_t^j$ *with*	
		$\ln(R\&D/Y)_t^j$	$\Delta \ln(R\&D/Y)_t^j$	$\ln(R\&D/Y)_t^j$	$\Delta \ln(R\&D/Y)_t^j$
Market economy	Fra	0.62	-0.70	0.02	0.30
	Ger	-0.81	0.53	0.46	-0.44
	UK	0.39	-0.16	0.00	-0.11
Manufacturing	Fra	-0.53	-0.44	0.72	-0.05
	Ger	-0.85	0.19	0.55	-0.33
	UK	-0.58	0.09	-0.02	-0.44

Pairwise correlations dropping observations for which any one of the series has missing observations.

and in growth rates. The correlations between the log-level of R&D intensity and the technology gap appear to be high (0.5 to 0.85) and in 4 out of 6 cases, negative. The correlation between the log-level of R&D intensity and technology growth is high en positive in 3 out of 6 cases. In the other 3 cases, correlation is nearly zero. A possible explanation for low correlation is that the economic or social conditions under which R&D is conducted hamper a positive effect from R&D on the absorption of leading technology. Using the growth rate of R&D intensity, correlations are sometimes rather low and signs are not stable across sectors and countries. This suggests that within the context of the growth model, the log-level of R&D is a relatively better measure. Correlations with

RSE intensity are also sometimes very low and not stable. This is not displayed in Table 4.2 to save space.

To sum up, I cautiously conclude that the correlations seem to support the expectations from the theoretical model. There is a positive correlation between the growth rates of labour productivity and capital intensity. The growth rate of technology seems to be related to the technology gap and the US technology growth rate. There also seems to exist a relationship between the log-level of R&D intensity and the technology gap and technology growth, though the exact relationship is not clear beforehand.

4.4.2 Stationarity

The theory underlying econometric estimation with time series is based on the assumption that series are weakly or covariance stationary. Hence, the mean and autocovariances of the series should not depend on time. When this condition is violated, standard inference procedures do not apply when nonstationary series are included in the regressions.

Most variables enter the empirical model in log-differenced form (that is, growth rates). If the time series on productivity y, capital intensity K/L and technology A in log-levels are integrated of order zero (denoted $I(0)$), regression in log-differenced form will introduce moving average errors. If the series are integrated of order one, log-differencing is appropriate. Finally, if the time series on the log-level of R&D intensity are stationary, the technology growth function can be estimated with the R&D intensity in log-levels.

I apply the Augmented Dickey-Fuller (ADF) test. The ADF test estimates a regression of a time series y_t in first differences on y_{t-1}, p lagged difference terms of y, and exogenous regressors such as a constant or a trend. This is used to test the null hypothesis of a unit root (coefficient of y_{t-1} is zero) against the alternative (coefficient of y_{t-1} is negative).[15] ADF test results should be interpreted with some care. There are no uniformly powerful tests for unit roots. The power of the ADF test depends on a number of factors. The time span of 40 years is not very long, which could weaken the power of the test. But possible structural breaks in the time series influence the test results. I did not apply a trend break test as I did in the previous chapter, because the time span is relatively short in historical perspective. Moreover, historically, the Second World

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[15] This coefficient is equal to the autocorrelation coefficient ρ minus one.

War is the main trend break after which the Western European countries converged to the US productivity level. The current time series start in 1956. Second, if a time series is integrated of order higher than 1, there is more than one unit root, whereas the ADF test assumes one single unit root. Third, the null of a unit root is often accepted if the coefficient of y_{t-1} is about, but not exactly zero.[16] Furthermore, data peculiarities in the dynamic panel might also affect the test results. However, scrutinizing these peculiarities requires an in-depth data analysis, while the aim of the current chapter is to test the theoretical growth model.

Table 4.3 displays the results of ADF tests on the time series in log-levels. It shows mixed results with some time series being stationary and

Table 4.3: ADF test results, 1956-1996 $^{(a)}$

		I(.)	s.l.	C	T	lag	I(.)	s.l.	C	T	lag
		$\ln(Y/L)_t^j$					$\ln(K/L)_t^j$				
Market sector	Fra	0	*	C		3	2				1
	Ger	0		C		2	0		C		1
	UK	1		C		1	1		C	T	1
Manufacturing	Fra	0	*	C		2	0		C		2
	Ger	0		C		3	2		C	T	4
	UK	1		C		1	1		C	T	2
		$\ln(R\&D/Y)_t^j$					$\ln(RSE/H)_t^j$				
Market sector	Fra	0		C		1	1	*	C		1
	Ger	0	*	C		1	1	**			1
	Uk	1				1	1				1
Manufacturing	Fra	1				1	2		C		1
	Ger	1		C		1	0	*	C	T	3
	Uk	1				1	0	**			1
		$\ln A_t^j$					$\ln(A_t^j/A^{US})$				
For both sectors	Fra	2				1	0	*	C		1
	Ger	2	**	C	T	3	0	*	C	T	1
	UK	0		C	T	3	2				1
	US	2				1					

The ADF statistic is to the left of the McKinnon critical value at 1% significance level (s.l.). Otherwise, * = 5%; ** = 10%. The constant C and and trend T are picked at 5% significance level.

(a) Sample period for $\ln A_t^j$ Germany 1960-1996; sample $\ln(R\&D/Y)_t^j$ for German manufacturing 1966-1996; sample $\ln(RSE/H)_t^j$ in market sector 1964-1996 for France, 1966-1996 for Germany and UK; in manufacturing 1973-1996 for all three European countries.

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[16] That is, if the autocorrelation coefficient ρ is about, but not exactly, one.

others non-stationary with one or two unit roots. These results do not clearly indicate whether and how to transform the non-stationary time series to avoid the spurious regression problem.

However, a linear combination of two (or more) non-stationary series might be stationary, i.e., cointegrated (Engle and Granger, 1987). As their relationship does not depend on time then, this combination can be interpreted as a long run equilibrium relationship among the variables. The non-stationary series in log-levels can then be used in estimation of the model.

Table 4.4 presents the results of Johansen cointegration tests on combinations of two time series in log-levels. Most combinations appear to be cointegrated. Productivity can be regressed on capital intensity and technology in either log-levels or growth rates. As the model is in growth rates, the estimation is carried out on the growth rates of the variables.

Table 4.4: Johansen cointegration test results, 1956-1996

	1st series	2nd series	France	Germany	UK
Productivity growth function					
Market sector	$\ln(Y/L)_t^j$	$\ln(K/L)_t^j$	yes	not valid	yes
	$\ln(Y/L)_t^j$	$\ln A_t^j$	yes	yes	yes
Manufacturing	$\ln(Y/L)_t^j$	$\ln(K/L)_t^j$	not valid	yes	yes
	$\ln(Y/L)_t^j$	$\ln A_t^j$	yes	yes	yes
Technology growth function					
	1st series	2nd series	France	Germany	UK
For both sectors	$\ln A_t^j$	$\ln A_t^{US}$	no	yes	yes
	$\ln A_t^j$	$\ln(A_t^j/A_t^{US})$	yes	yes	yes
Market sector	$\ln A_t^j$	$\ln(R\&D/Y)_t^j$	yes	yes	yes
	$\ln(A_t^j/A^{US})$	$\ln(R\&D/Y)_t^j$	not valid	not valid	no
Manufacturing	$\ln A_t^j$	$\ln(R\&D/Y)_t^j$	yes	yes	yes
	$\ln(A_t^j/A^{US})$	$\ln(R\&D/Y)_t^j$	yes	yes	no

'Yes' indicates that series are cointegrated. 'Not valid' indicates that both series are integrated of order zero, so that a cointegration test is not appropriate.

A few combinations of time series appear not to be cointegrated. First, the combination of the French technology level A^{Fra} and the US technology level A^{US} is non-stationary. This suggests that technological progress in France follows another growth path than in the US. Second, the combination of the British technology gap and its R&D intensity level in both the market and manufacturing sector appeared to be not stationary. A possible explanation is that in the UK other, non-R&D, forces play a stronger role than R&D effort itself in the realization of the potential to catch up.

To sum up, the unit root and cointegration tests on the time series properties of the data show that estimation of the theoretical growth model of Section 4.2 can be carried out with some care. In estimation, I assume that the time series are cointegrated.

4.4.3 Estimation method

From a theoretical viewpoint, it is interesting to disentangle the impact of international technology diffusion on growth and the role of R&D in reducing the technology gap. This is the main reason that the productivity and technology growth equations are estimated separately.[17]

As in the theoretical model the right hand side variable technology growth $\Delta \ln A_t^j$ in the productivity growth function is endogenous, I apply weighted two stage least squares (WTSLS). One instrumental variable is the lag of the growth in capital intensity, with capital measured in efficiency units, $\Delta \ln(AK/L)_{t-1}^j$. This variable correlated not too strongly with the residuals in a weighted least squares (WLS) estimation of the productivity growth function.[18] Together with a constant, the identification condition for IV estimation is satisfied.[19] The technology growth function is estimated with WLS.

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[17] Because the two growth equations may contain mutual intertemporal links, it might have been estimated simultaneously. However, estimations revealed no significant results for the technology growth function. A possible explanation is that one or both of the equations is misspecified. Another cause may be that the panel data display hidden dynamics causing estimation problems.

[18] Other variables, such as the lag of technology growth $\Delta \ln(A)_{t-1}^j$ or the lag of the growth of capital intensity $\Delta \ln(K/L)_{t-1}^j$, were more strongly correlated with the WLS residuals.

[19] With two right hand side variables, two instrumental variables including the constant is needed. Moreover, all exogenous right-hand side variables should be listed as instruments for a given equation. In the productivity growth equation, this is the capital variable.

In initial estimations, it appeared that the Durbin Watson (DW) statistic values were often lower than the lower bound according to the bounds test for DW (Hill et al., 2001, pp.273-274). This indicated severe positive autocorrelation. The presence of autocorrelation implies the estimated coefficients are consistent, but not efficient (Baltagi, 2001, p.81). Including first order autoregressive AR(1) terms or lags of the endogenous LHS variable might increase the efficiency of the parameter estimations. However, the use of AR(1) terms is not generally accepted in estimations with panel data. Panel data dynamics can easily be confused with serial correlation. Moreover, it is possible that the model's restrictions on the coefficients led to the low DW values. This seems to hold for particularly the productivity growth function. Therefore I present estimations without AR(1) terms for the productivity growth function, though this implies that the estimators are less efficient. For tentative comparison, Table D.1 presents WLS estimations with AR(1) terms, which thus do not account for the endogeneity of the technology growth variable, and WTSLS estimations with AR(1) terms. The WLS estimation of the technology growth function includes AR(1) terms.

The productivity growth equation is estimated with the lagged capital variable, as this produced statistically significant estimations for the coefficient α. Lagging of the capital variable may be theoretically explained by a 'time-to-build' argument: it takes some time for investment to become productive. Lagging the technology variable does not improve the estimation results for the productivity growth function.[20] Furthermore, an intercept is left out of both the equations. The aim is to test the theoretical model, in which no intercept is present.

Furthermore, I estimate common coefficients α and γ and country specific coefficients α^j and γ^j. I apply the Wald test to find whether the null hypothesis of a common coefficient would be rejected for the alternative of country specific coefficients. The focus of the current chapter is to find to what extent countries differ in these important parameters. In order to restrict the number of parameters to be estimated, I chose to estimate a common coefficient β and ψ. But as countries, by definition, differ in the distance to the technology frontier, the long run technology gaps z^j are country-specific estimates. Furthermore, in the estimation of the technology growth function, I applied different proxies for R&D effort n_t to test the sensitivity of the estimations. Finally, the main estimations for both the productivity growth function and the

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[20] These results follow the correlations in Table 4.2.

technology growth function concern the period 1966-1996, as the time series on manufacturing R&D start only by 1966.

The absence of an intercept, the restrictions imposed by the model on coefficients, and estimation with WTSLS implies that the coefficient of determination does not apply. The standard error of the regression is likely to have more predictive power (Pindyck and Rubinfeld, 1998, p.95).

4.5 Estimation results

The productivity growth equation (4.6) and technology growth equation (4.7) with the speed of diffusion (4.8) are estimated with pooled data for the three European countries in the period 1966-1996. The US are the presumed technology leader. Section 4.5.1 presents the estimation results for the productivity growth equation, and Section 4.5.2 the estimation results for the technology growth equation.

4.5.1 The productivity growth function

Table 4.5 displays the WTSLS estimation results for the productivity growth function for the period 1966-1996.

Capital and technology Estimation of a common coefficient α indicates that the size of the capital share in output is slightly less than one third for the market sector, and 38% for the manufacturing sector, the remainder being accounted for by technological progress. The impact of capital accumulation appears to be relatively large in manufacturing, compared to agriculture and services. This may be explained by the relatively higher capital intensity of the manufacturing sector. In previous studies (e.g. Mankiw et al., 1992), the long run share of capital in aggregate output was found to be about one third. The estimation results of the current growth model are not too far off these earlier estimates.

International differences The estimations show that the three countries differ in the role capital intensity and technology play in the development of labour productivity. Moreover, the countries also differ at sectoral level in to what extent capital contributes to growth. The coefficient estimates show that the capital share varies across countries in

Table 4.5: WTSLS estimation productivity growth function, 1966-1996 (t-values between brackets)

$$\Delta \ln y_t^j = (1-\alpha)\Delta \ln A_t^j + \alpha \left[\Delta \ln(K/L)_{t-1}^j + \Delta \ln A_{t-1}^j\right] + u_t$$

	market sector		manufacturing	
$\hat{\alpha}$ (common), impact capital intensity growth				
	0.29 (4.73)		0.38 (6.47)	
$\hat{\alpha}$ (country-specific), impact capital intensity growth				
France		0.23 (1.75)		0.34 (2.62)
Germany		0.40 (4.25)		0.38 (3.70)
UK		0.23 (2.30)		0.40 (4.65)
Observations	93	93	93	93
Mean dependent variable				
France	3.60	3.60	4.38	4.38
Germany	3.43	3.43	3.54	3.54
UK	3.01	3.01	3.72	3.72
Standard error regression				
France	3.30	3.39	3.61	3.64
Germany	2.46	2.31	2.83	2.83
UK	2.45	2.48	2.41	2.40
Durbin Watson				
France	0.40	0.38	0.63	0.62
Germany	0.64	0.79	1.04	1.04
UK	0.99	0.99	1.21	1.22

Instrumental variables are the lag of the capital growth variable and a constant. The estimated values of the autocorrelation coefficient for the manufacturing sector are all significantly smaller than 1 according to Wald tests.

the range from 25 to 40%, the remainder being accounted for by technological progress. The Wald test does not reject the null hypothesis of a common coefficient α for both the market sector and manufacturing sector. However, the aim of the model estimation is to show to what extent countries differ in the impact of technology diffusion on economic performance. It is still economically senseful to consider the international differences in the slope parameter α.

Compared to the other two countries, the role of technology is smallest in the German market sector, with a capital share of 40%. In France and the UK, the estimated capital share is nearly one quarter. Carlin (1996) argues that capital plays a relatively large role in the German economy. But this does not imply that technology is relatively unimportant for Germany. Rather, it may be partially embodied in the capital stock. The German flexible skill-intensive production system in the 1970s and 1980s benefited from decreasing costs in information processing and automation (Broadberry, 2005).

In the manufacturing sector, the impact of capital intensity growth is comparatively small in France (with capital share 0.34) and large in the UK (0.40). The comparatively small role of technology growth in UK manufacturing may be explained by the relatively large focus on capital accumulation, first by introducing American capital intensive mass production systems without much own innovations, and later on the copying of the German skill intensive automation system and Japanese flexible production systems (Broadberry and Crafts, 2003). The literature also suggests that the slow productivity growth of the UK is partially determined by lack of innovations despite a high science base, due to ill-designed policies (cf. Chapter 3 and Nickell and Van Reenen, 2001).

Other subperiods Estimations for other subperiods, namely 1956-1996 and 1973-1996 (see Table D.2), show common coefficient estimates for α which do not differ much from the estimates for the period 1966-1996. This suggests that the quantitative role of capital compared to technology does not change much over time. This seems to be counter-intuitive in the light of the economic-historical experience. Crafts and Toniolo (1996), for instance, consider the high-growth period 1956-1973 in Western Europe as an exceptional period in historical perspective. After 1973, growth slowed down and European economies returned to their long run growth paths. However, it is difficult to identify to what extent qualitative changes in capital and technology affect their quantitative role.

4.5.2 The technology growth function

Table 4.6 presents estimation results for the technology growth function for the period 1966-1956.

Technology growth in leader country US The estimated coefficients β for US technology growth $g_{\hat{A}_t^j}$ indicate a significant, positive impact of US technology growth on the European countries' technology growth. The estimated value is remarkably low. The growth model as-

Table 4.6: WLS estimation technology growth function, 1966-1996 (t-values between brackets)

$$\Delta \ln A_t^j = -\left(\psi^j + \gamma^j [n_t^j]\right)\left(\ln A_{t-1}^j - \ln \hat{A}_{t-1} - z^j\right) + \beta \Delta \ln \hat{A}_t + u_t$$

$$u_t = \rho u_{t-1} + \varepsilon_t$$

$$n_t^j = \ln(R\&D/Y)_t^j$$

	market sector		manufacturing sector	
$\hat{\beta}$, *impact US technology growth*				
	0.22 (2.88)	0.22 (2.87)	0.20 (2.59)	0.24 (3.14)
$\hat{z}$, *long run gap with US technology*				
France	-0.46 (-3.22)	-0.58 (-5.05)	-0.55 (-6.15)	-0.58 (-5.93)
Germany	-0.37 (-9.45)	-0.37 (-12.09)	-0.32 (-6.99)	-0.33 (-9.21)
UK	-0.52 (-8.88)	-0.53 (-12.44)	-0.52 (-8.82)	-0.54 (-15.22)
$\hat{\gamma}$ *(common), impact R&D intensity on speed of diffusion*				
	34.34 (2.59)		33.22 (3.08)	
$\hat{\gamma}$ *(country-specific), impact R&D intensity on speed of diffusion*				
France		50.27 (2.40)		40.97 (2.94)
Germany		47.46 (2.53)		40.68 (3.15)
UK		49.03 (2.46)		49.96 (3.09)
$\hat{\psi}$, *impact constant on speed of diffusion*				
	-89.50 (-2.48)	-129.61 (-2.37)	-51.70 (-2.87)	-66.09 (-2.90)
$\hat{\rho}$, *autocorrelation coefficient*				
France	0.82 (12.90)	0.81 (12.02)	0.78 (9.57)	0.76 (9.52)
Germany	0.90 (11.55)	0.89 (10.30)	0.78 (9.33)	0.74 (7.34)
UK	0.94 (19.42)	0.94 (19.22)	0.96 (20.52)	0.92 (18.10)
Observations	93	93	90	90
Mean dependent variable				
France	2.34	2.34	2.24	2.24
Germany	1.66	1.66	1.64	1.64
UK	2.08	2.08	2.02	2.02
Standard error regression				
France	0.89	0.88	0.88	0.88
Germany	0.43	0.42	0.40	0.40
UK	0.54	0.55	0.56	0.53
Durbin Watson				
France	2.19	2.12	2.17	2.25
Germany	1.07	1.21	1.44	1.57
UK	0.83	0.80	0.83	0.85

The estimated values of the autocorrelation coefficients $\hat{\rho}$ were all significantly below 1 according to the Wald coefficient test.

sumes that in the long run growth rate differences in technology between the leading and following country disappear, that is, β should approach value 1. The low values for β suggest that the period under consideration is too short to reveal long run values, or that idiosyncratic shocks move the follower economies from their equilibrium paths.

Alternatively, the result may be interpreted as that even in the longer run, technology growth rate differences remain to exist. This might be explained by the differences in technology systems and innovation systems. If these international differences do not change, growth rate differences remain to exist. The difference in the estimates for β between the market sector and manufacturing sector is negligible. This is probably because the technology level is measured with the total domestic patent stocks for both the market sector and manufacturing.

Long run technology gap The estimates for the long run technology gaps z_j are statistically significant. The parameter values are negative, with European economies being technology laggards. The long run gap is smallest for Germany and largest for France (cf. Figure 4.4). However, as the estimated coefficient values for US technology growth β are rather low and the European countries are probably not on their long run growth path, the estimated values for z_j might not be the actual long run values. Or it may be that the international differences in technology systems and innovation systems determine the technology gaps. The differences between the market sector and manufacturing are small probably because the technology level is measured for both sectors with the same patent stock.

R&D and the speed of diffusion What impact does R&D have on the speed of absorption of US technology? In Table 4.6, R&D effort n is proxied by the log-level of R&D expenditures per unit of value added, $\ln(R\&D/Y)$. Because it is in log-levels, the estimated values of the parameters γ and ψ are rather large. However, they are statistically significant.

For both the market sector and manufacturing, the estimated common coefficients γ for the log-level of R&D intensity are positive. This indicates that R&D effort, given the technology gap in the previous year, has a positive effect on the speed of absorption. Assuming that R&D effort provides absorptive capacity, the post-war Western European countries apparently experienced incentives to realize the potential in their technology gaps with the US by means of R&D. They apparently succeeded in the absorption of US technology, as their technology levels increased.

In contrast, the estimates for the constant ψ are negative. This indicates that, given the technology gap, without R&D effort the distance of the followers to the US frontier would increase. A possible explanation is that if the European economies do not invest in R&D while the leader US continues to innovate, their technology gaps with the US will increase in the long run. Investment in own R&D is probably a necessary condition to prevent stagnation and decline in follower countries.

The sectoral differences for the estimated common coefficient γ for R&D are negligible. But the constant ψ has a much larger impact in the market sector than in manufacturing (this holds particularly for France and Germany). Apparently, a lack of R&D investment, given the technology gap, has a larger negative impact in non-manufacturing sectors than in manufacturing sectors. A possible explanation is that barriers to adoption are higher in non-manufacturing sectors than in manufacturing. For instance, production systems or market conditions in manufacturing might resemble each other more across Western countries than in non-manufacturing sectors. Then non-manufacturing sectors are more in need for R&D to absorb leading technologies and not to fall further behind.

International differences In Germany, R&D effort has a comparatively smaller impact than in the other two countries. This holds for both non-manufacturing and manufacturing sectors, though the impact of R&D does not differ much between French and German manufacturing. The Wald tests also cannot not reject the null of a common coefficient for R&D, in both the market sector and manufacturing.

One might speculate that the small impact of R&D in Germany is linked to the comparatively small distance of Germany to the US technology frontier and its comparatively high R&D intensity level. On the basis of these variables it may be suggested that the innovation system in Germany is more effective and efficient than in France and the UK. This implies that Germany relatively less in need for R&D (which provides absorptive capacity) to absorb US technology.

Alternatively, one might argue that the small German distance to the US technology frontier implies that the technology still to be absorbed is more complex and more difficult to absorb. Then putting R&D into the absorption process might relatively less easily increase the speed of absorption. In this case, France and the UK have the advantage of greater technological backwardness. This would imply that they experience a comparatively faster technological catching up than Germany.

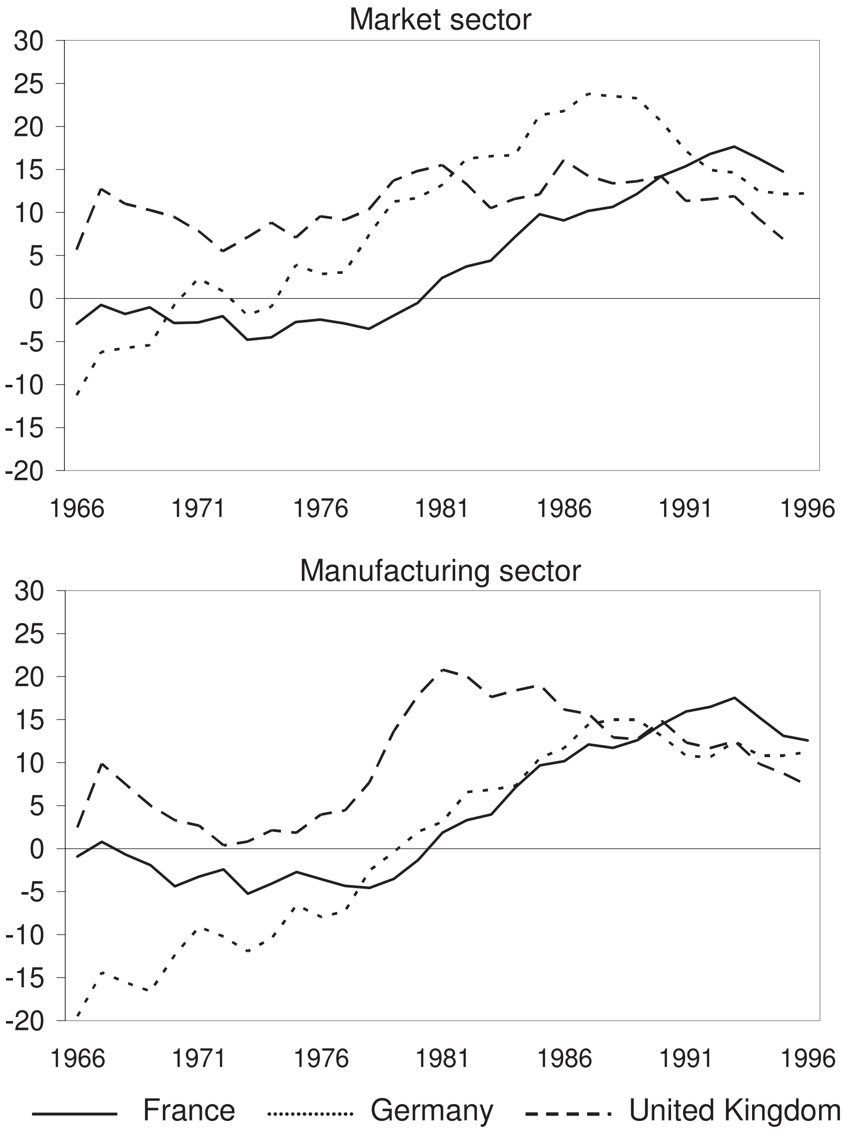
However, the development of the technology gaps and the speed of absorption in the three European countries between 1966 and 1996 suggest this is not the case. The composite time-varying speed parameter λ_t^j has been positive throughout the whole period for the UK in both the total market sector and manufacturing sector (Figure 4.5). The speed parameter became positive after 1980 for France and in the 1970s for Germany, signalling convergence to the US technology level from then on. France and Germany increased their speed of absorption during the period under consideration, while the UK speed of absorption stagnated after 1980.

That Germany might have a more effective and efficient innovation system than France but particularly the UK is in line with the economic literature on institutions in these countries. Post-war (West-)Germany is described as a coordinated market economy with long run relationships between employers, employees and customers at state level (Eichengreen and Iversen, 1999). It is supposed to have a strong research network of universities, applied research institutions, trade unions and firms. Its human capital institutional system is characterised by a widely spread dual vocational, work-based apprenticeship system (Broadberry, 2003a; O'Mahony, 2004). The link between education and the occupationally structured labour market is relatively direct (Buechtemann and Verdier, 1998). Moreover, the work organization within firms has a cooperative form, allowing for incremental innovations from the work floor.

In contrast, the large central state regulation in France restricted the influence of the fragmented labour unions and weak employer organisations (Eichengreen and Iversen, 1999). This probably made research and education institutions relatively less efficient. Up to the early 1980s, there was a strong dichotomy between public research and firms, and large public programmes and nationalized applied research institutions were directed by the government (Mustar and Laredo, 2002). Higher education in France was centralised and elitist, with an internal labour market (Buechtemann and Verdier, 1998). Work organization in firms was rather hierarchical. A typical French problem is the relatively large share of unskilled labour in the labour force.

Figure 4.5: Estimated speed of diffusion, 1966-1996

$$\hat{\lambda}_t^j = \hat{\psi} + \hat{\gamma}^j \left[\ln(R\&D/Y)_t^j\right]$$



Finally, the postwar UK liberal market economy suffered from strong deregulation. The government only occasionally sought for dialogue with weak labour unions and employer organisations (Eichengreen and Iversen, 1999). The UK could not exploit its high quality science base as applied research institutions did not play a firm role (Nickell and Van Reenen, 2001). Research was mainly a competition between organisations and between firms, with a short run focus. This led to relatively more radical innovation than in Germany and France, but also to more dispersion in innovation performance across industries. Like in France, general academic education had a larger prestige than vocational education (Buechtemann and Verdier, 1998). The traditional apprenticeship system was restricted to the crafts, being deregulated by the government. Only by the 1990s, vocational education was rehabilitated, with standardisation and national certification (O'Mahony, 2004). Like France, the UK knows an internal labour market and hierarchical work organization within firms. In contrast to Germany and France, it has a low share of engineers in the labour force. Moreover, its business R&D spending per unit of value added stagnates from the late 1970s onwards (Figures 4.2 and 4.3).

Other subperiods Estimation for other subperiods, namely 1956-1996 for the market sector and 1973-1996 for both the market sector and manufacturing, show estimates for the common coefficients γ and ψ which differ from the estimates for the period 1966-1996 (Table D.3). The estimate for γ in the market sector between 1956 and 1996 is rather low. A possible explanation may be that in the early post-war period between 1956 and 1966 the European economies caught up by means of capital accumulation rather than R&D effort. They still had to build up their R&D institutions (cf. Chapter 3). In the period 1973-1996, in contrast, the estimate for γ is higher than that for the period 1966-1996. By 1973, R&D efforts in the European countries had increased substantially. Apparently, R&D had a larger impact on the absorption of US technology. However, on the basis of the estimates for ψ, it might be argued that at the same time, institutional barriers to absorption of US technology had increased. This seems to be in line with economic-historical studies on institutional problems in Western Europe after 1973 (Eichengreen, 1996).

Other proxies for research effort I estimated the technology growth function with alternative proxies for research efforts to see whether the parameter estimates are robust. Applying the growth rate of R&D intensity as a proxy for n do not show significant results (Table D.4). But using the log-level of RSE per hour worked, statistically significant parameter estimates show up. The results might be explained by that a follower country needs a critical mass (or stock) of research effort in order to increase the speed of absorption, rather than how fast it accumulates its R&D effort.

4.6 Conclusions

By means of estimating a macro-economic growth model, the current chapter aimed to make explicit to what extent differences in international technology diffusion affect economic growth differences, given that countries have different technology systems and innovation systems. In the growth model, R&D effort by a follower country enhances absorption of foreign leading technology. With absorption, the follower may reduce its technology gap with the leader, increasing its technology level and labour productivity.

The model was estimated for the market sector and manufacturing in France, Germany and the UK in the period 1956-1996. The US was the productivity and technology leader by the end of World War II. From the US, advanced technology diffused to the three European economies. Comparative developments in labour productivity show France and Germany caught up with the US in non-manufacturing sectors, but remain at 80% of the American level in manufacturing. The UK is the laggard in both non-manufacturing and manufacturing sectors during the whole period under consideration. In technology, the US remains the leader. Meanwhile, the R&D efforts of Germany and France largely expanded, while in the UK, the R&D intensity stagnated compared to that in the US. The estimations of the macro-economic growth model showed the following:

First, labour productivity growth is statistically significantly affected by the growth of the technology level. Technology appears to account for a share in output varying between 60 to 75 percent in France, Germany and the UK. Capital intensity growth has a complementary role by supporting and embodying innovations. Moreover, the role of technology varies across the three European countries and sectors. Compared to the other two countries, the role of technology is smallest in German non-manufacturing and UK manufacturing, and largest in French manufacturing.

More importantly, the estimations show that given the technology gap in the previous year, R&D effort has a positive impact on technology growth. But without R&D effort, the three European countries will lag further behind the US. An interpretation of this result is that the US continues to invest in innovation, and if followers do not invest in R&D to absorb the US technology, they will fall behind. This effect seems to be larger for non-manufacturing sectors than for manufacturing. This might be explained by larger barriers to adoption in non-manufacturing sectors, such as larger differences in production systems or market conditions across countries.

In Germany, R&D effort has a comparatively smaller impact on technology growth than in the other two countries. This holds for both non-manufacturing and manufacturing sectors. It may be suggested that the innovation system in Germany is more effective and efficient than in France and the UK, as the German distance to the US technology frontier is smaller and R&D intensity comparatively higher. This implies that Germany relatively less in need for R&D (which provides absorptive capacity) to absorb US technology. This explanation is in line with the economic-historical literature, which states that German research and education institutions are stronger than in France and the UK.

Furthermore, the long run distance to the technology frontier in the US differs across the three European countries. The long run technology gap is smallest for Germany and largest for France. These results have two potential explanations. First, the European economies are possibly still not on their long run growth path. Or, second, due to differences in technology systems and innovation systems with the US, growth rate differences will persist in the long run. Without a change in the technology system and the innovation system, the followers will diverge from the leader in the long run. Finally, the growth of the technology level in the three European economies is positively affected by the technology growth rate in the US. However, the estimates indicate that there exist technology growth rate differences between leader and followers, which will persist in the long run conditional on the international differences in technology systems and innovation systems.

The model is estimated for a certain period, given that technology systems and innovation systems differ across countries. The technology growth rate differences between the followers and the US may disappear in the longer run if the technology systems and innovation systems of the followers change. The international differences in the distance to the US technology frontier indicate that some countries will need more adjustment of their technology systems and innovation systems than other countries.

During the transition to the long run equilibrium, R&D appears to be necessary for the followers to absorb US technology. The impact of R&D and international technology diffusion appears to differ across countries. Absorption of foreign technology is no simple copying, but implies adjustment to the own technology system and innovation system. Some seem to have been more successful (Germany) than others (the UK). One of the problems in testing a growth model is that subtleties which occur in the joint diffusion of techology and institutions are not easy to grasp by the model. But the research results exactly point to the importance of taking into account the long run forces of technology systems and innovation systems. Historically, the technology diffusion mechanism works via the diffusion of institutions.

The impact of R&D and technology diffusion also differs across sectors. However, the current measure of the technology level (total domestic patent stocks for both the market sector and manufacturing) does not reveal differences in the way foreign leading technology is absorbed by various sectors. Foreign technology might be channelled directly into the sector for which the technology was intended to. For instance, new knowledge in telecommunication developed in the US might be transferred into the telecommuncation branch in France. Alternatively, foreign technology may be transferred into the sector only via other domestic sectors. This may occur because the particular technology does not immediately reveal sector-specific applications but needs to be adjusted to local circumstances. An example is ICT, a now widely applicable technology. The next chapter highlights these issues by modeling different diffusion channels which transfer leading technologies into an industry in a follower country.